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Review Article

A Review of the Application of Biopolymers on Geotechnical Engineering and the Strengthening Mechanisms between Typical Biopolymers and Soils

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The use of admixtures in soils to improve their properties has been implemented since ancient times. Diverse conventional admixtures such as lime, fly ash, and cement have been added to soils. Also, petrochemicals and bacteria are increasingly used for soil improvement and soil stabilization both mechanically and chemically. However, the conventional admixtures for soils cause significant environmental problems (e.g., CO_2 emission). Biopolymers can increasingly replace the conventional admixtures for the application of soil improvement and soil stabilization. Numerous studies have been conducted in the past decades to investigate the suitability and efficiency of various biopolymers for soil improvement. This paper focuses on the properties of the most common biopolymers (xanthan gum, gellan gum, agar, polyacrylamide, and guar gum) and gives the mechanism of biopolymer-treated soils for soil improvements proposed by researchers.

1. Introduction

Improving soil properties is a long-standing attempt and development in geotechnical engineering. From research related to civilization in the past, researchers noticed the use of many soil improvement techniques such as surface compaction, drainage methods, vibration methods, precompression and consolidation, grouting and injection, chemical stabilization, soil reinforcement, and geotextiles and geomembranes [1]. Ancient civil engineering techniques are the use of natural materials (e.g., mud, bitumen, and straw) and binders for storing water, for controlling the flooding near the rivers, and for various fundamental needs. In ancient Rome, Roman concrete made from a mixture of a natural pozzolan material (i.e., volcanic ash), aggregates, and a binder such as gypsum or lime was used primarily to build durable structures [1–3]. After the Industrial Revolution, ordinary Portland cement was invented for soil stabilization [4–6]. After the Postwar reconstruction, chemical mixtures and industrial by-products started to be investigated and developed. Since the Kyoto Protocol, all engineering disciplines are constantly striving to suppress environmental concerns including environmental protection [7]. The current generation has recognized that indiscriminate development has worsened the environment. We therefore inevitably take corrective action with sustainable technology for nature.

Ordinary Portland cement has dominantly been used for construction purposes (e.g., infrastructures and urbanization) with various advantages (e.g., low cost, high strength, durability, and workability) [8]. For example, in 2012, approximately 3.8 Gt of cement is consumed worldwide in just one year [9]. On the other hand, excessive dependence and excessive use of cement have a great impact on the environment as mentioned in the previous paragraph [8]. Particularly, air pollution due to carbon dioxide (CO_2) emissions, a major culprit of greenhouse gases generated in large quantities during cement production, is a serious situation. In order to mitigate this CO_2 production, geotechnical engineers have started to focus on bio-mediated soil improvement technologies.

Bio-mediated soil improvement techniques have been introduced to reduce carbon dioxide (CO_2) emission during the process of cement production [10–12]. The possible environmentally friendly materials (e.g., biopolymers) [13–16] and methods (e.g., microbial-induced calcite precipitation (MICP) [17–19]) are an alternative to conventional soil treatment and improvement techniques (i.e., mechanical improvement and chemical treatment). Particularly, biopolymers as biodegradable polymers have been investigated as a construction material for soil improvement [20–22].

In recent years, most studies on the applicability of biopolymers have been published with experimental results and their analyses, numerous theoretical explanations, and rare case studies of practical implementation. This paper provides a review of the application of biopolymers in geotechnical engineering using the most recent studies. Moreover, strengthening mechanisms between typical biopolymers (i.e., xanthan gum, gellan gum, agar, polyacrylamide, and guar gum) and soils based on microscopic interparticle interactions are summarized.

2. Application of Biopolymer in Geotechnical Engineering

2.1. Biopolymers

2.1.1. Xanthan Gum. Xanthan gum is an anionic polysaccharide that is formed by *Xanthomonas campestris* bacterium [3, 23–25]. When xanthan gum is stirred by both cold and hot water, xanthan gum solution will be highly viscous because of its viscous hydrogel formation with water [26]. Figure 1 shows the xanthan gum production process, and Figure 2 shows the xanthan gum production processes in detail. Xanthan gum is generally used as a viscosity thickener because it absorbs water molecules through hydrogen bonding [23, 27]. The usage of Xanthan gum in geotechnical engineering is to reduce the permeability of sandy soils by filling their pores [28] and enhance the soil erosion resistance by increasing water retention [2].

Chang et al. [20] showed that a small amount of xanthan gum-treated Korean red-yellow soil enhanced soil erosion resistance and improved the vegetation cultivation. Xanthan gum-treated soil has strong water adsorption during precipitation season and high soil moisture retention during the dry season [30]. Another recent study has studied possibilities for preventing liquefaction in sandy soils [30]. Im et al. investigated dynamic properties of xanthan gum with typical Korean sand (i.e., Jumunjin sand) through resonant column (RC) tests [30].

2.1.2. Gellan Gum. Gellan gum in the polysaccharide group is a high-molecular-weight polymer produced by the bacterium *Sphingomonas elodea* (formerly known as *Pseudomonas elodea*) [27, 31, 32]. Also, gellan gum is generated by four molecules: (1,3)-β-D-glucose, (1,4)-β-D-glucuronic acid, (1,4)-β-D-glucose, and (1,4)-α-L-rhamnose as shown in Figure 3 [27]. Low acetyl gellan gum (e.g., at low concentration: 0.05–0.25%) with thermal and acid stability can form gels [32, 33], and the network formation of biodegradable hydrogels crosslinked with gellan gum and chitosan has thermal stability up to 250 degree celsius [33]. Gellan gum with the pore filling effects has been investigated to decrease the permeability and improve the strength of shallow soils [1]. Another recent study has investigated the interactions between gellan gum and soils [32]. Chang and Cho [31] investigated the shear strength and cohesion of gellan gum-treated sand-clay mixtures increase with increasing the overburden stress levels through direct shear tests.

2.1.3. Agar. Agar is obtained from the red algae (e.g., *Gelidium*, *Gracilaria*, and *Gelidiella*) or red seaweeds [33]. Figure 4 shows the chemical structure of agar. Large quantities of *Gelidium* have been harvested in Spain, Portugal, and Morocco. Some *Gracilaria* are found in the cold waters of Chile and Canada, and some species live in warm, tropical climate water in Indonesia. *Gelidiella* is mainly distributed in India, mostly in the tropical and subtropical waters.

When agar forms gels, it provides rigid textures and has been used as a stabilizer [27]. Agar has hydrophobicity that excels in the solubility and the gelling of the agar. The melting point of agar is 85–95°C, and gelling point is 32–45°C. Gel strength of 1.5% agar at 20°C is 70–1000 g/cm^3. The viscosity and the average molecular weight of 1.5% agar at 60°C is 10–100 centipoise and 36–144 kDa, respectively [33].

2.1.4. Polyacrylamide. Polyacrylamide (PAM) is a water-soluble polymer, and Figure 5 shows the structure unit of PAM polymer. PAM is widely used for EOR, water treatment, and soil amendment effects because PAM is more effective and relatively inexpensive [36–38]. For EOR, partially hydrolyzed polyacrylamide (HPAM) solution with 0.5 wt.% NaOH showed a better sweep efficiency than polymer flood [37]. In wastewater treatment, a low cationic polyacrylamide (4 mg/L PAM) to high rate algal pond (HRAP) treating wastewater in New Zealand achieved at least 50% improvement of total suspended solid (TSS) removal [39]. In agricultural purposes, more flocculation efficacy and stable aggregates of PAM solution (compared to water) reduce water erosion [30].

2.1.5. Guar Gum. Guar gum is a polysaccharide and is obtained from the seeds of *Cyamopsis tetragonoloba* [25, 41]. The general composition of guar gum is galactomannan (75–85%), moisture (8–14%), protein, fiber, and ash [42]. Guar gum has high molecular weight and is a water-soluble polymer. Guar gum molecule consists of α-D-galactose and β-D-mannopyranose backbone as shown in Figure 6 [41].

The addition of guar gum (0.25–2% concentration) reduced the permeability of silt and sand and increased the cohesion stress of sand. Moreover, Chudzikowski [41] proved the pore filling effect of guar gum (2% concentration

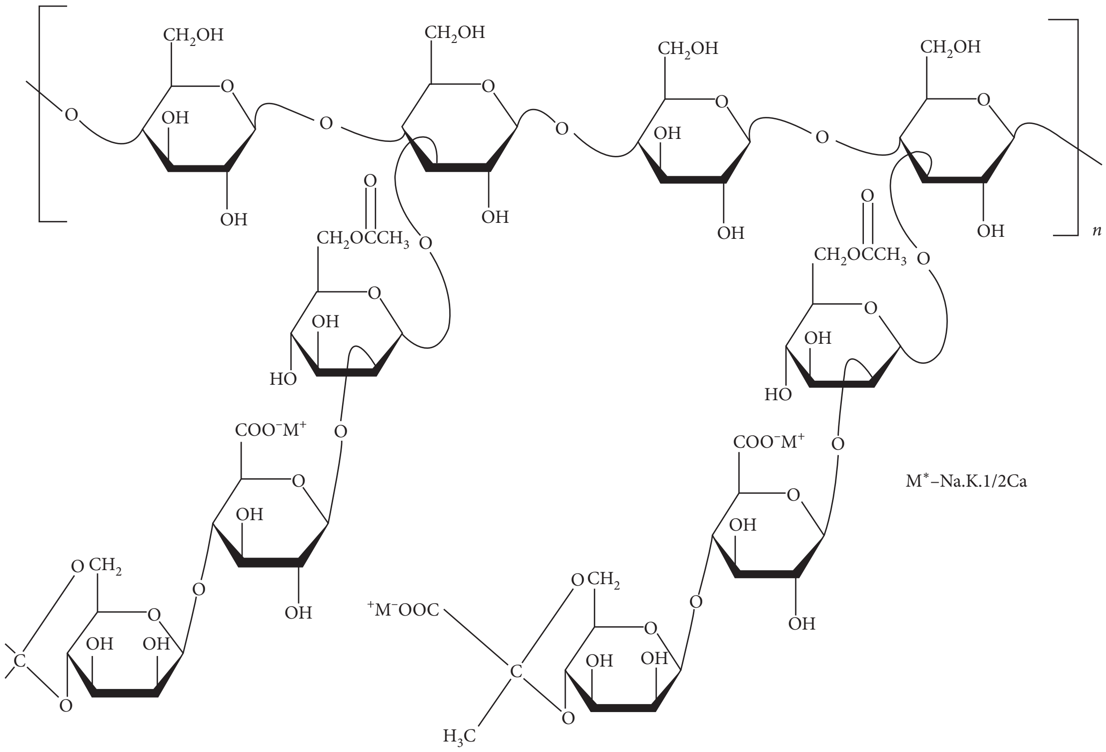


Figure 1: The structure of *Xanthomonas campestris* [26].

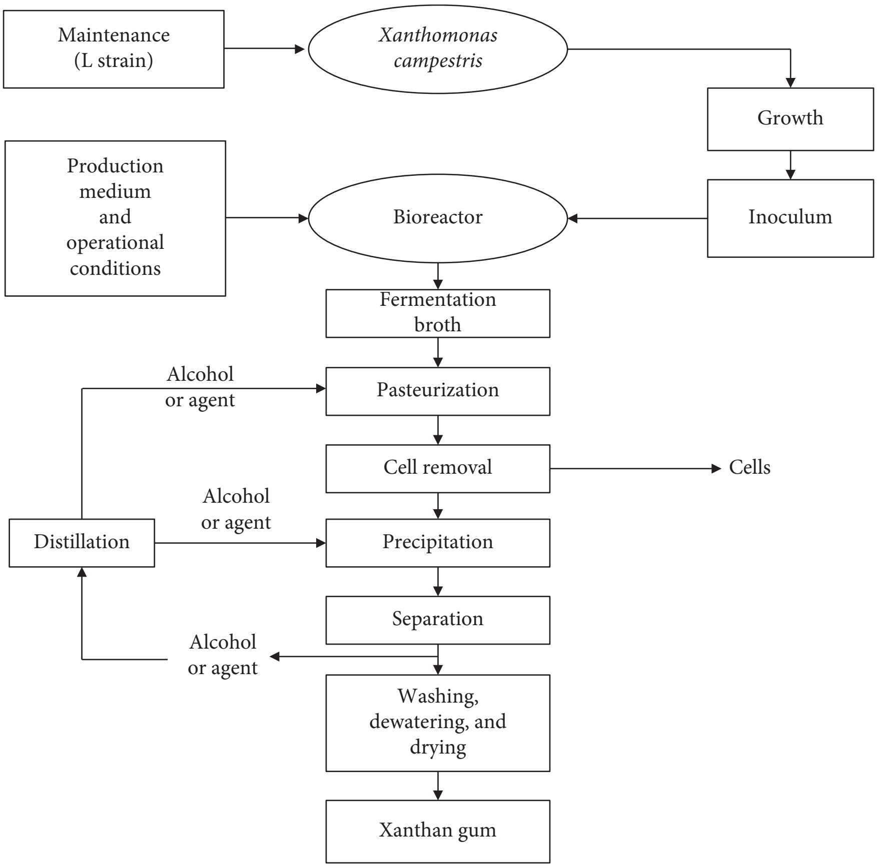
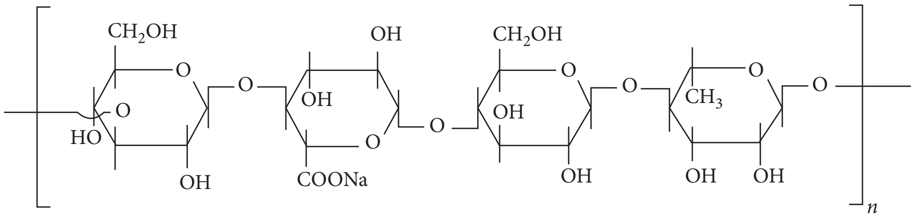


Figure 2: Xanthan gum production process [26].



→3)-β-D-Glcp-(1→4)-β-D-GlcpA-(1→4)-β-D-Glcp-(1→4)-α-L-Rhap-(1→

Figure 3: The repeating unit of gellan gum [34].

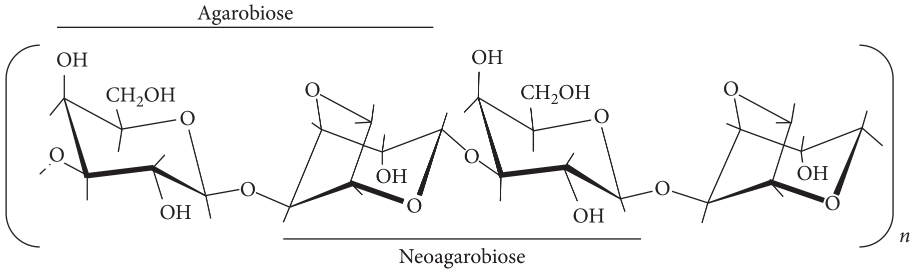


Figure 4: The chemical structure of agar [35].

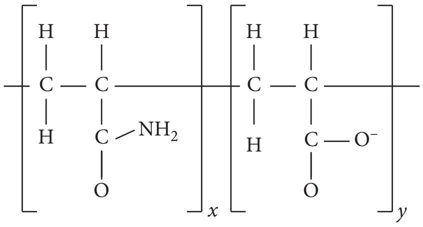


Figure 5: The structure unit of polyacrylamide (PAM) polymer [40].

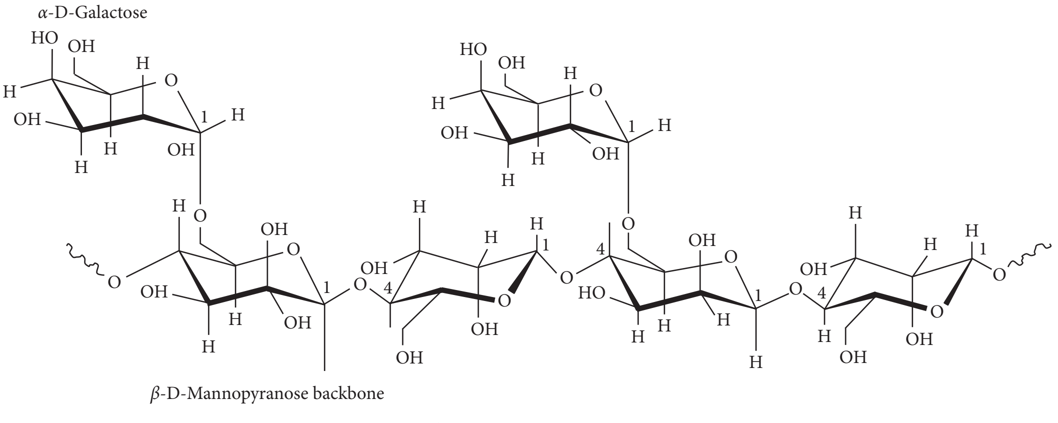


Figure 6: The structure of guar gum [39].

after curing time of 5 weeks) between the soil particles by scanning electron micrographs (SEM).

2.2. Development Process of Biopolymers for Soil Stabilization. The engineered treatment of soil in construction is always developed since the beginning of human civilization. In ancient civil engineering, engineers used natural materials and binders such as mud, straw, lime, and especially cement for soil improvement. After the Industrial Revolution, ordinary Portland cement was invented, and then it has improved as cement-based concrete. Humans have become interested in the usage of chemical mixtures and industrial byproducts during postwar reconstruction.

After Kyoto protocol 2005, geotechnical engineers and researchers have a distinct social need for sustainability in geotechnical engineering because massive carbon dioxide as the main culprit of global warming is released during the manufacturing of cement, which is widely used for soil improvement [43]. To lessen the amount of CO_2 emissions, several environmentally friendly materials have been proposed for soil improvement. The materials include geopolymer, MICP, biopolymers, and so on.

Geopolymer was invented in 1979 and has been continuously applied in various fields such as fire-resistant wood panels, insulated panels and walls, thermal shock refractory, and geopolymer-based cement and concrete. Especially, researchers have studied the usage of geopolymers in the field of cement and concrete. On the other hand, little studies have been done on soil improvement using geopolymers.

The MICP method as a biological process implements to precipitate calcium carbonate for filling the voids in the soil and then induces bonds between soil particles [3, 31, 44–46]. MICP has improved the engineering properties of soil (e.g., sand), rather than non-bio-mediated treatment methods [47, 48]. The MICP method improves the properties of coarse soil particles (e.g., sand or silt) [44, 49–52]. However, the MICP method may be an inefficient method for improving the soil strength when the fine particles are 25% or more in the soil distribution composed of fine and coarse soil particles [53].

Unlike geopolymers and MICP, numerous studies subjected to the usage of biopolymers in geo-materials have been investigated for soil stabilization. Biopolymer-treated soils enhance their soil strengthening [31], reduce their hydraulic conductivity [54], and improve soil dynamic properties and the resistance to soil erosion in geotechnical engineering [30]. The direct use of biopolymers in soil has some advantages over traditional biological soil treatment methods, and the direct use of exocultivated biopolymers for soil treatment overcomes some shortcomings of other approaches such as the need for microbial and nutrient injection, time for cultivation and excrement precipitation, and inappropriateness with clayey soils. Moreover, biopolymers can be used as a substitute for cement that emits greenhouse gases because biopolymers are easily found and are harmless in nature. Biopolymers in polysaccharide group recently have been examined for use in geotechnical engineering. Particularly, the characteristics of five common biopolymers are summarized in Table 1. Table 2 summarizes the physicochemical properties of commercial biopolymers.

2.3. Physicochemical Properties of Each Biopolymer. Table 2 summarizes the physicochemical properties of each biopolymer. Common biopolymers are generally powder and soluble in water. Only PAM is insoluble in water. Table 2 also shows the experimental results for molecular weight, moisture, ash, viscosity, melting point, and gelling point. Although each biopolymer is of the same biodegradable polymers, we need to have an engineering judgement to use these properties appropriately because the physiochemical properties are different.

2.4. Potential Applications of Each Biopolymer. Table 3 summarizes the potential applications of xanthan gum-treated soils in geotechnical engineering. Through various studies, xanthan gum also has the potential to be applied to wind erosion control, soil remediation, soil grouting, and vegetation growth improvement in drylands. Xanthan gum generally treats coarse soils such as sand. Tables 4 and 5 summarize the potential application of gellan gum-treated soils and agar-treated soils, respectively. Table 6 shows the applications of PAM in various fields. Lastly, Table 7 summarizes the potential applications of guar gum-treated geomaterials (e.g., mine tailings and clay).

Figure 7 shows the prices of five representative biopolymers for soil stabilization. Xanthan gum and PAM are less than $2000/ton, which is relatively cheaper than the other three biopolymers. On the other hand, gellan gum and agar gum have a large price difference depending on the quality of the biopolymers, and therefore, a preliminary investigation for soil stabilization should be thoroughly conducted. Table 8 shows the detail price of the biopolymers.

3. Strengthening Mechanisms of Biopolymer-Treated Soils

3.1. Xanthan Gum. Figure 8 shows the peak strength behavior of xanthan gum-treated sand with varied xanthan gum gel phase (initial, dried, and re-submerged) [60]. The initial state means that the xanthan gum-treated sand specimens were immediately tested as soon as they were prepared in the disk-shaped mold (60 mm in diameter and 20 mm in height). The dried state represents that xanthan gum-treated sand specimens were tested after drying them at room temperature for 28 days. Lastly, the re-submerged state means that half of the dried sand specimens were submerged in distilled water at room temperature for 24 hours before testing.

Even a very small amount of xanthan gum (i.e., 0.5%) in the sand affects the change in strength behavior of xanthan gum-treated sand. Increasing the content of xanthan gum on the initial gel of xanthan gum increases the cohesion, but the friction angle is constant. For the dried gel phase of xanthan gum, both the cohesion and friction angle increase with adding more xanthan gum content to the sand because of the formation of xanthan gum biofilm on the surface of sand particles and viscous hydrogels of xanthan gum that result in the pore clogging [54, 60, 67, 76]. At the re-submerged condition, the peak friction angles of xanthan gum-treated sand decrease with more xanthan gum content (from 1% xanthan gum) because the interaction (e.g., surface friction and interlocking) between interparticles is reduced by higher swelling pressure generated by the half of pure dried sand specimens swell [60].

The residual interparticle cohesion and friction angle values of xanthan-treated sand at initial, dried, and re-submerged conditions are shown in Figure 9. The residual shear strength properties of xanthan gum-treated sand depend on the condition of xanthan gum gel phase. At initial condition, the cohesion and friction angle of xanthan gum-treated sand are constant, regardless of xanthan gum content. Such constant values might be affected by the van der Waals interaction (i.e., hydrogen bonding) [60]. However, at dried condition, the residual shear strength properties (both cohesion and friction angle) of xanthan gum-treated sand increase with adding more xanthan gum content. Simultaneously, at the re-submerged condition, the residual cohesion of xanthan

Table 1: The general advantages of five common biopolymers for soil stabilization.

Biopolymer	Chemical composition	The advantages of biopolymer	References
Xanthan gum	$C_{35}H_{49}O_{29}$	(i) Decrease the permeability (ii) Retain the amount of water due to strong hydrogen bonding	[3, 25, 55]
Gellan gum	—	(i) Enhance soils strength and soil durability under thermogelation treatment	[20]
Agar	$(C_{12}H_{18}O_9)_n$	(i) Improve the shear strength of soil due to curing time effect (ii) Rapid gelation and no chemical reaction during soil improvement technique	[11, 25, 56]
Polyacrylamide (PAM)	$(C_3H_5NO)_n$	(i) Increase water infiltration (ii) Decrease soil erosion due to PAM hydrogels	[3, 57–59]
Guar gum	—	(i) Reduce the level of bleeding of the ground granulated blast-furnace slag (GGBS) cement grouts (ii) Reduce the permeability (iii) Increase the shear strength parameters	[55, 60]

Table 2: The physicochemical properties of commercial biopolymers.

Biopolymer	Xanthan gum	Gellan gum	Agar	Polyacrylamide (PAM)	Guar gum
Physical state	Dry, cream-colored powder	Water soluble, off-white powder	Gelidium	—	White with pale yellow tinge, nonionic and hydrocolloidal in water
Solubility	Soluble in water	Soluble in water	Freely soluble in hot water at temperature above 85°C	Not water-soluble polymer	Soluble in water
Molecular weight	—	—	36–144 kDa	10^5–$>10^7$ Da	10^6–2×10^6 [39]
Moisture (%)	8–15	—	≤20	—	8–14 [39] 10.28 [61]
Ash (%)	7–12	7.0	—	—	0.72 (acid insoluble) 0.85 (minerals after combustion)
Viscosity	13–35 cp (15.8 s^{-1}, $C_p = 1$ g/L, $T_D = 25$ Celsius, $T_M = 25$ Celsius)	8,000 mL/g in 0.1 M KCl	10–100 cp (1.5% at 60°C)	—	1,200 Pa·s at 2% concentration [62] 10,000 cP [63]
Melting point	—	—	85–95°C	—	—
Gelling point	—	—	32–45°C	—	—
References	[26]	[28, 64]	[25, 33, 65]	[38, 40]	[39, 55, 59, 61]

Table 3: Potential application of xanthan gum-treated soils.

Application	Soil type	Test	Summary
Wind erosion control	SM	Wind erosion test	(i) Xanthan gum-treated sand against wind erosion is effective, even during daylight [66]
Soil remediation	Sand	Pressurized pumping flow system	(i) Xanthan gum-treated sand shows good plugging effects by decreasing the permeability of sand [67]
Soil grouting	SP	Experimental design of laminar flow into soil mass	(i) For xanthan gum injection into the soil, its injection efficiency decreases with an increase in the injection pressure [68]
Vegetation growth improvement in drylands	SP	Soil-water retention test	(i) 0.5% xanthan gum used to the soil shows enough sufficient effect for vegetation growth in drylands [13]

Note. SM and SP indicate poorly graded nonplastic silty sand and poorly graded sand in Unified Soil Classification System (USCS) classification, respectively.

Table 4: Potential application of gellan gum-treated soils.

Applications	Soil type	Test	Summary
Geotechnical earthquake-related soil management	Sand (SP) clay (CH) mixtures	Laboratory vane shear test and direct shear test	(i) Gellan gum-treated sand-clay mixtures increase both cohesion and friction angle [31]

Note. SM (poorly graded nonplastic silty sand) and CH (heavy clay) in USCS.

Table 5: Potential application of agar-treated soils.

Applications	Soil type	Test	Summary
Liquefaction remediation	SM	Consolidated undrained monotonic triaxial tests	(i) Increasing agar in silty sand improves the shear strength and cohesion [69]

Note. SM (silty sand; Gs = 2.65; void ratio = 0.85–1.09) in USCS.

Table 6: Applications of PAM in various fields [38].

Applications	Property	Molecular weight [Da]	Concentration [mg/L]	Ionic form	Consumption [tons/yr]
Oil and gas extraction [38, 70–72]	Viscosity enhancement for EOR, drag reduction for high volume hydraulic fracturing (HVHF)	10^6–3×10^6	30–3000	Nonionic, anionic, and cationic	2500–7500 for HVHF; N.A. for EOR
Soil conditioning for erosion control [40, 73]	Adsorption	10^6–2×10^6	<10	Nonionic, anionic	900–1800

Note. https://www.nature.com/articles/s41545-018-0016-8/tables/2.

Table 7: Potential applications of guar gum-treated geomaterials.

Applications	Material	Test	Summary
Mine tailings stabilization	Mine tailings (69% alumina silicate, 30% quartz, and 1% pyrite)	(i) Fall cone test (followed the British standard BS1377)	(i) The increase in guar gum added to the mine tailings increases their liquid limit and undrained shear strength [62, 74]
Slope stability	CH and CL	(i) Linear shrinkage test (ii) Direct shear test (iii) Unconfined compression strength test (UCS)	(i) Guar gum-treated soils reduce their shrinkage potential (ii) Both guar gum-treated soils (CH and CL) significantly increase their shear strength parameters such as cohesion and friction angle [75]

Note. CH (heavy clay) and CL (lean clay) in USCS.

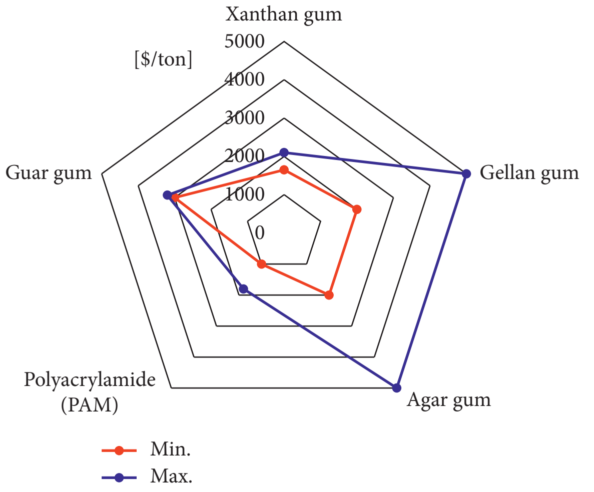


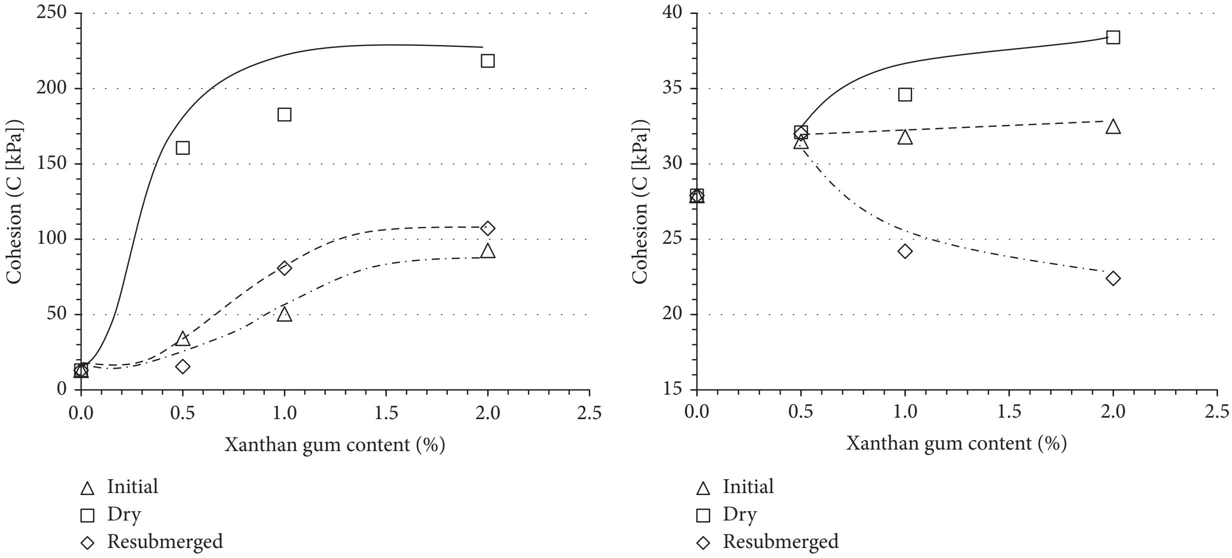
Figure 7: Typical price of commercial biopolymers (unit: $/ton).

gum-treated sand increases with higher xanthan gum contents, whereas the residual friction angle of xanthan gum-treated sand decreases with more xanthan gum contents. In particular, the lower viscosity of xanthan gum hydrogels at higher strain level might explain the decrease of friction angle of xanthan gum-treated sand as pseudoplasticity behavior of xanthan gum hydrogels at high strain level [60].

Figure 10 represents the soil-water characteristic curve for Ottawa 20–30 sand saturated with a xanthan gum solution (Figure 10(a)) and the SEM image of Ottawa 20–30 sand in xanthan gum. The van der Waals force between fluid (i.e., xanthan gum solution) and the solid surface (i.e., sand surface) will decide the thickness of surface water film. The SEM image shows xanthan gum solution attached to the Ottawa 20–30 sand surface (Figure 10(b)). This adhesiveness will explain that the matric suction to desaturated Ottawa 20–30 sand saturated with xanthan gum solution is greater than that of the sand saturated with water.

Table 8: Typical market price of commercial biopolymers.

Biopolymer	Price [$/ton]	Source: Alibaba
Xanthan gum	1,650–2,100	https://www.alibaba.com/product-detail/OTIS-xanthan-gum-of-food-grade_62238965217.html?spm=a2700.7724838.2017115.37.5ec76b89yZRGsC&s=p
Gellan gum	2,000–5,000	https://www.alibaba.com/product-detail/CAS-71010-52-1-Gellan-gum_62042700273.html?spm=a2700.7724838.2017115.96.1c1e49ffBkAtfU
Agar	2,000–5,000	https://www.alibaba.com/product-detail/Best-prices-food-grade-agar-agar_62042181620.html?spm=a2700.7724838.2017115.13.63bf7ce3npckx4&s=p
PAM	1000–1800	https://www.alibaba.com/product-detail/Water-treatment-chemical-flocculant-nonionic-anionic_60722226362.html?spm=a2700.7724838.2017115.1.4b51599575qEKw
Guar gum	3000–$3200	https://www.alibaba.com/product-detail/Guar-gum-Carboxymethyl-Hydroxypropyl-Guar-Gum_62003523110.html?spm=a2700.7724838.2017115.43.b8ba6108qYZafs&s=p



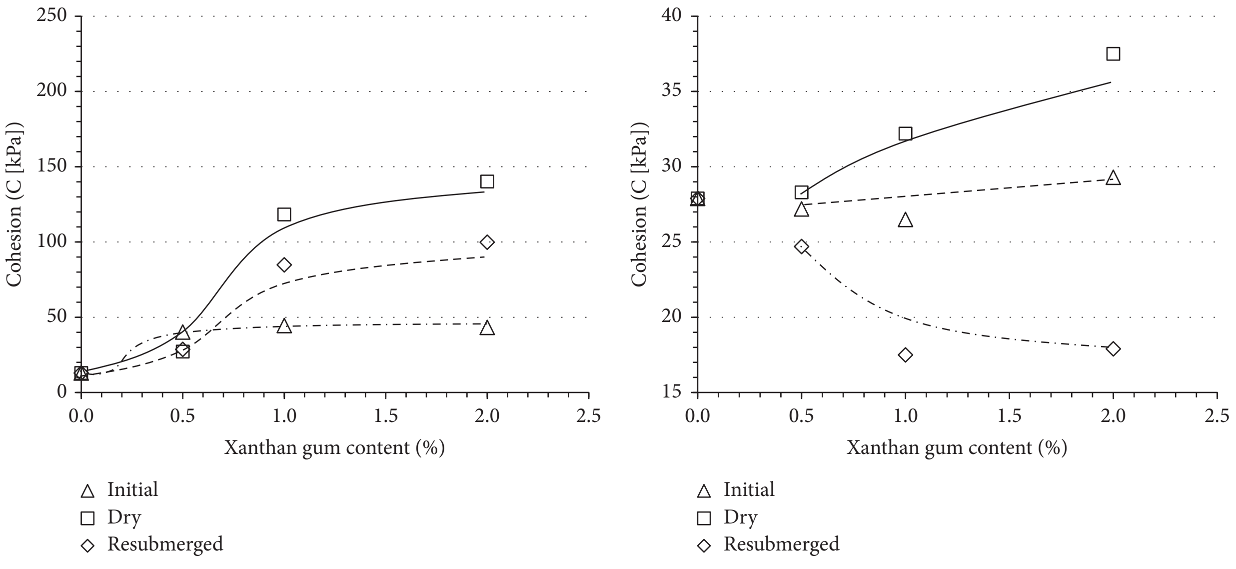
(a) (b)

Figure 8: Peak strength behavior of xanthan gum-treated sand: (a) cohesion; (b) friction angle [60].

3.2. Gellan Gum. Figure 11 shows the direct shear strengths of thermogelated gellan gum treated soils. Overall, both cohesion and friction angle of gellan gum-treated soils increase with higher gellan gum, except only pure sand (100% sand with no clay; SP in USCS). In Figure 11(a), a small quantity (1–5% gellan gum) of gellan gum in pure sand only dramatically increases its cohesion, whereas the friction angle of pure sand with the small amount of gellan gum is similar to that of pure sand without gellan gum.

Figures 11(b) and 11(c) are the result of a mixture of gellan gum added in proportion to sand and clay. The sand to clay ratio of the prepared specimen is 80 : 20 (SC in USCS) in Figure 11(b) and 50 : 50 (CL in USCS) in Figure 11(c). Overall, the cohesion and friction angle of gellan gum-treated sand-clay mixtures increases with a gradual increase of gellan gum ratio. Even 1% gellan gum in sand-clay mixtures dramatically increases both the cohesion and friction angle because gellan gum binds clay particles in several places, and the aggregated clay and gellan gum increase cohesion and friction angle [31]. 1% gellan gum in sand forms bridges between adjacent sand particles as shown in Figures 12(a) (spatial resolution: 500 micrometer) and 12(b) (spatial resolution: 50 micrometer).

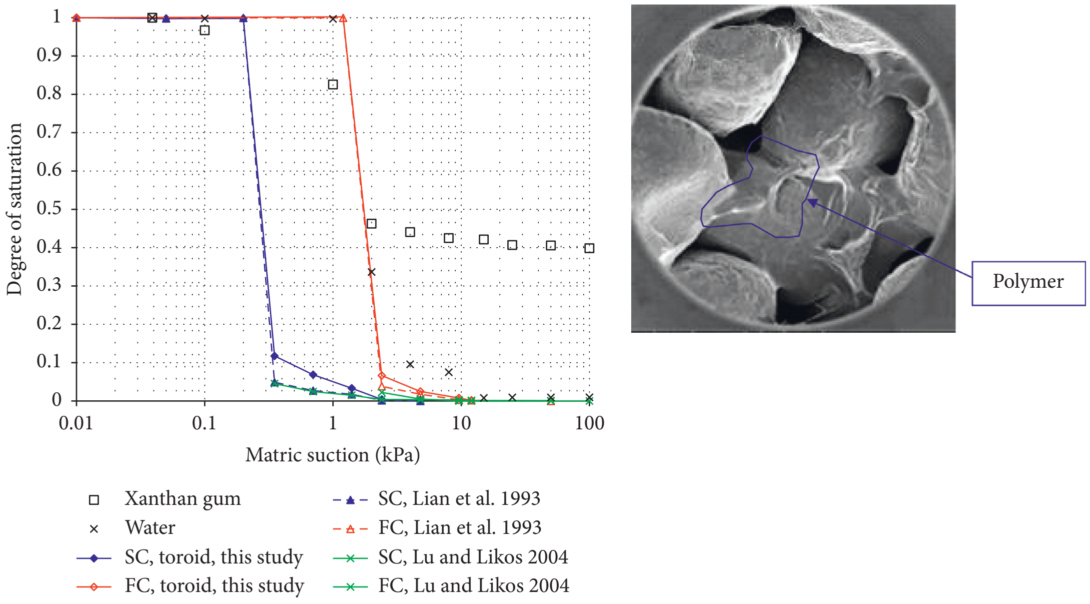
3.3. Agar. Figure 13 shows the unconfined compressive strength of air-dried-biopolymer-treated clayey soils (i.e., Korean residual soil) (Figure 13(a)) and sandy soils



(a)

(b)

Figure 9: Residual strength behavior of xanthan-treated sand: (a) cohesion; (b) friction angle [60].



(a)

(b)

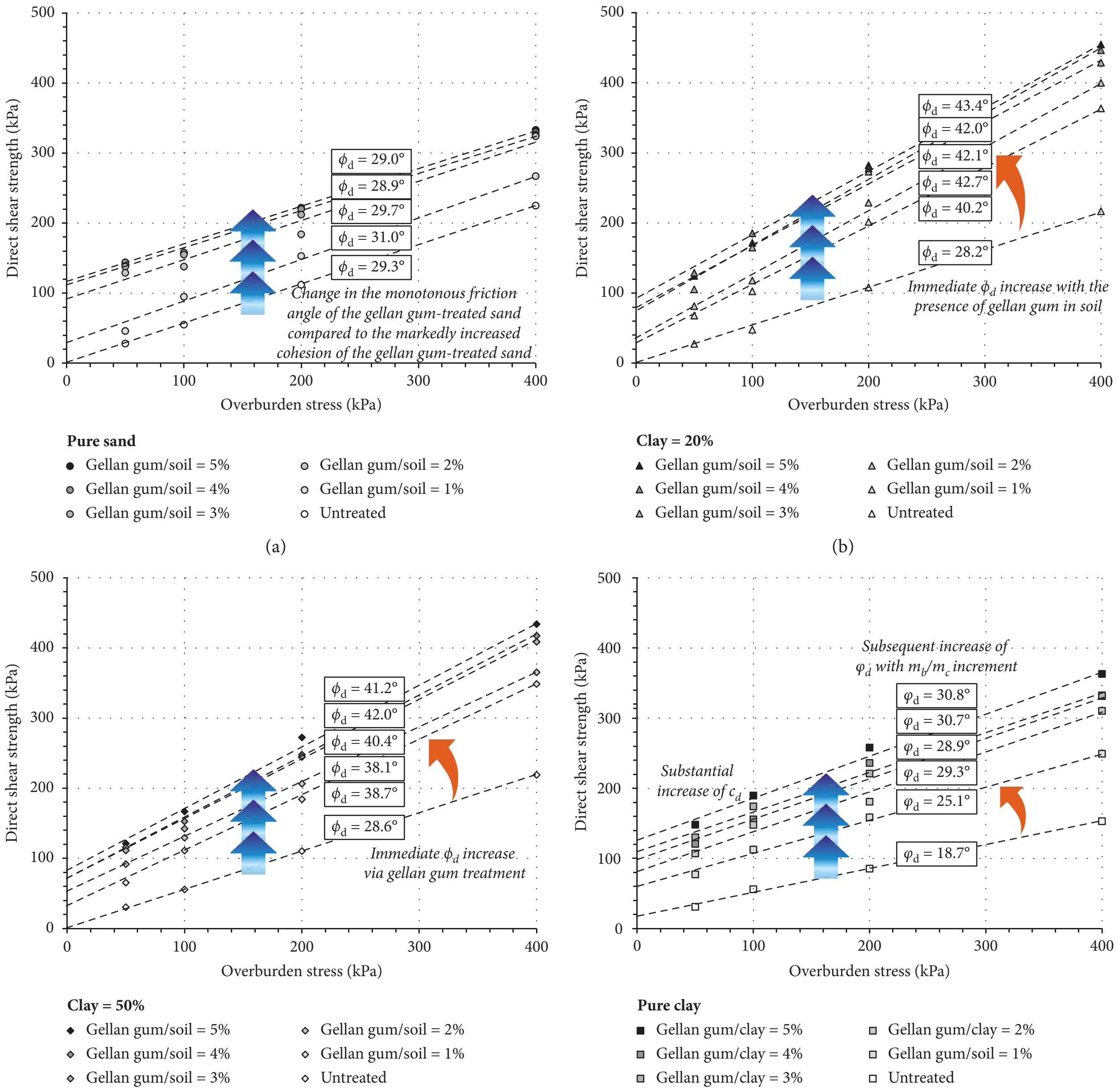
Figure 10: (a) Soil water characteristic curve for Ottawa 20–30 sand saturated with xanthan gum solution. (b) SEM image of Ottawa 20–30 sand in xanthan gum [42]. Note: SC = simple cubic packing; FC = face-centered cubic packing.

(Figure 13(b)) with time (i.e., up to 28 days). As the duration of air drying of biopolymer-treated soils increases, the unconfined compressive strength of clayey/sandy soil with biopolymers (i.e., gellan gum and agar) improves. The higher concentration of biopolymer improves the compressive strength values in both clayey and sandy soils.

SEM image of agar-clayey soil mixtures shows that agar gels cover massive mixtures of the clayey soil and agar because of the indirect interactions by long molecular structures of agar wrap clayey soil particles as shown in Figure 14 [27].

3.4. PAM. Figure 15 shows the relationship between pore saturation (i.e., the values of the displacement ratios) and flow rate in the air-saturated and decane-saturated silica micromodels (represented Ottawa sand). In order to perform the micromodel tests, air or decane (represented oil) fully filled the pores of micromodel. After filling all the pores, the micromodel tests were performed.

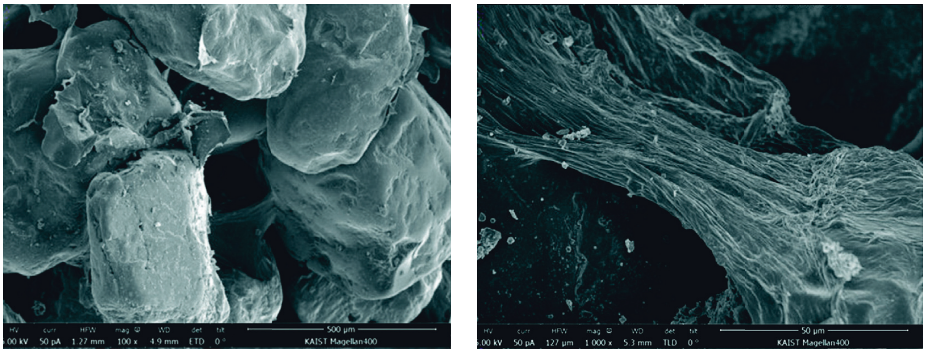
The pore saturation of the PAM solution in the air-saturated silica micromodel gradually increases with the faster flow rate (Figure 15(a)), whereas the effect of the



(a) (b)

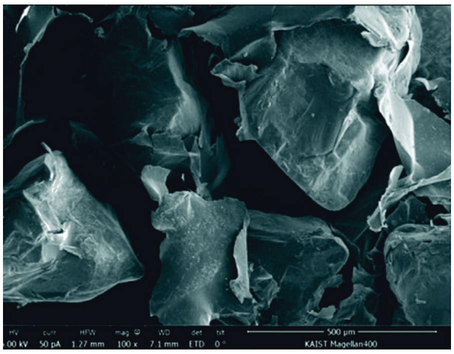
(c) (d)

Figure 11: Results of gellan gum-treated (thermogelation) soils using direct shear tests [31].



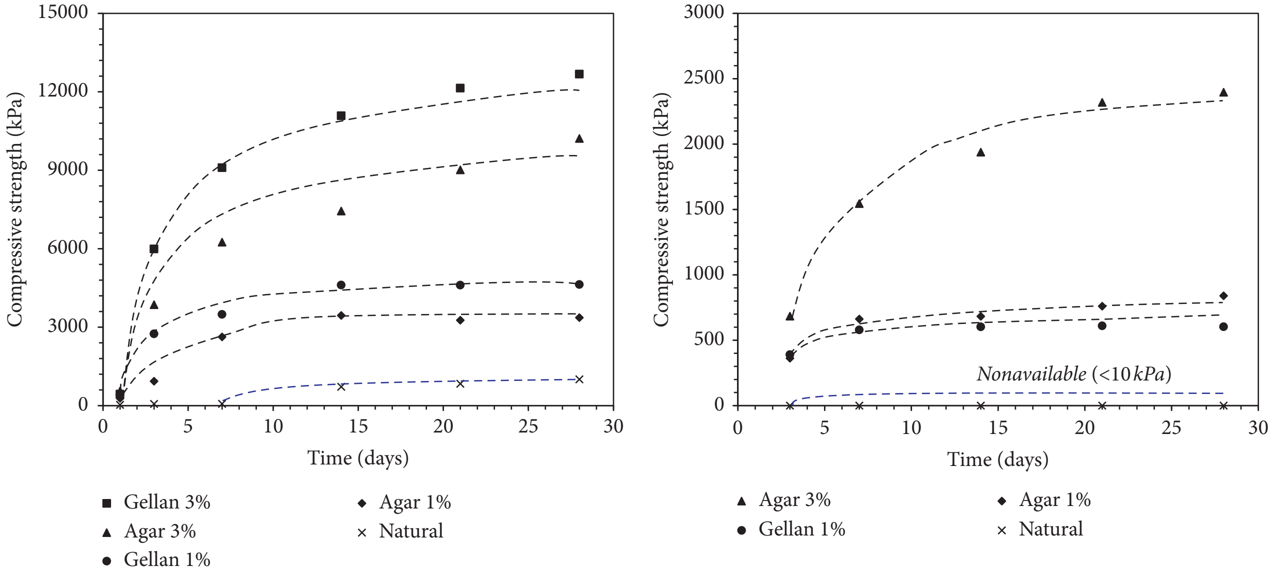
(a) (b)

Figure 12: Continued.



(c)

Figure 12: SEM images of 1% gellan gum-treated sand. (a) Before UTM testing (undisturbed). (b) Gellan gum films accumulated between particles (undisturbed). (c) After UTM testing (crushed) [77].



(a)

(b)

Figure 13: Unconfined compressive strength with time for (a) biopolymer-treated clayey soil and (b) biopolymer-treated sandy soil dried in air at room temperature (20 ± 2°C) [27].

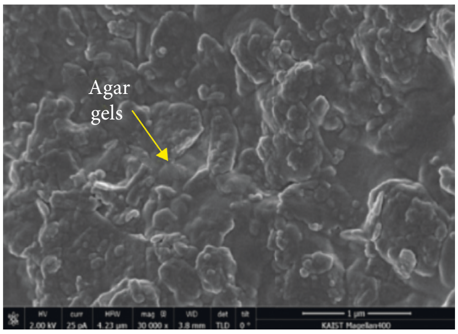


Figure 14: SEM image of agar-treated clayey soil [27].

PAM concentration is little. However, the pore saturation of the PAM solution in the decane-saturated silica micromodel suddenly increases at a flow rate of 1 μL/min (Figure 15(b)).

Moreover, the higher concentration of PAM does not always move more decane in decane-saturated micromodel. Therefore, to increase cost efficiency for soil remediation, it is best to increase the flow rate (i.e., the injection speed of

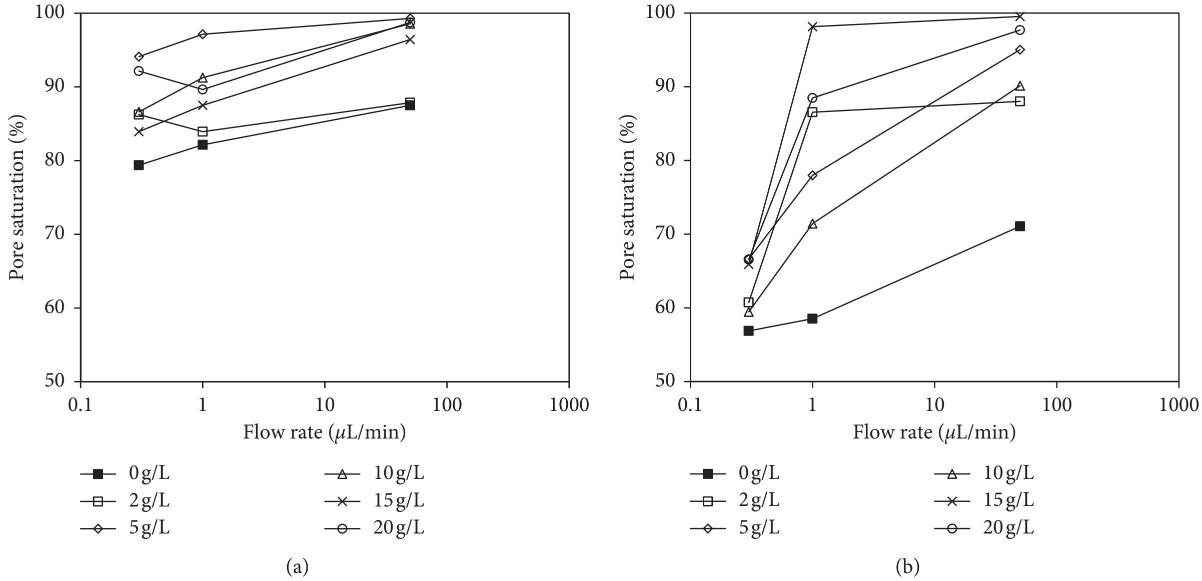


Figure 15: Pore saturation with respect to flow rate of PAM solution through microfluidic models in (a) air-saturated micromodel and (b) decane-saturated micromodels [58].

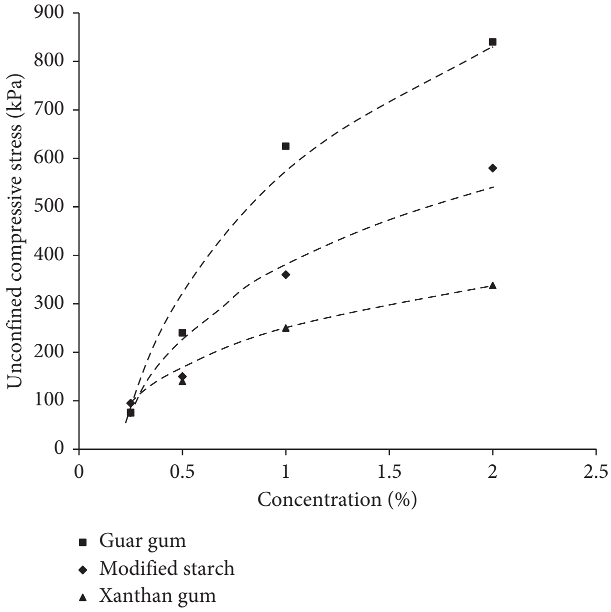


Figure 16: Effect of biopolymer concentrations on the unconfined compressive stress for silt/biopolymer mixtures after 5 weeks [55].

PAM solution into the decane-saturated micromodel), and only 5 g/L PAM can achieve a similar effect as the PAM concentration of more than 15 g/L [58].

3.5. Guar Gum. The unconfined compressive stress of silt/biopolymers (e.g., pure sand, guar gum, modified starch, and xanthan gum) with varied concentrations after 5 weeks of curing time is shown in Figure 16. Increasing biopolymer content in silt enhances the unconfined compressive stress of silt/biopolymers. Adding guar gum to silt is the best choice for increasing strength among the three biopolymers. This implies that the rate of increase in the shear behavior of biopolymer-treated silt depends on the type of biopolymer.

The failure envelopes of sand/biopolymers (e.g., pure sand, 2% guar gum, 2% modified starch, and 2% xanthan gum) after 5 weeks curing time are plotted by the direct shear tests as shown in Figure 17. The cohesion of biopolymer-treated sand is higher than pure sand. However, cohesion depends on the type of biopolymer. The cohesion of guar-gum treated sand is the highest among the three biopolymers.

SEM can assess the improvement in the shear strength parameters of sand/guar gum mixtures (Figure 18). Guar

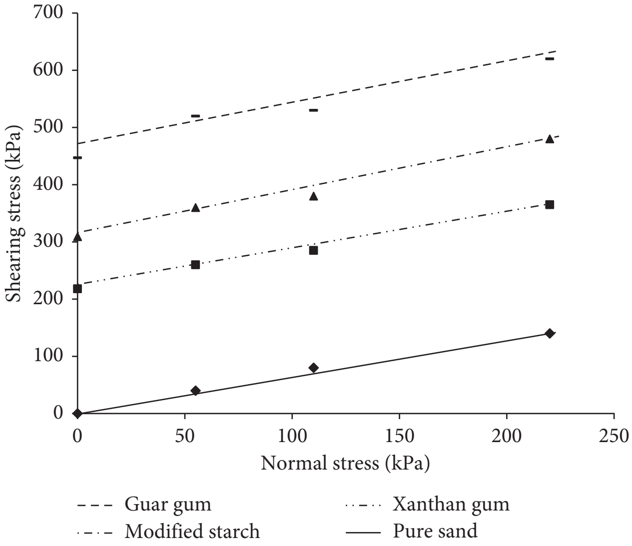


FIGURE 17: Effect of various biopolymers on the unconfined compressive stress for silt/biopolymer mixtures after 5 weeks [55].

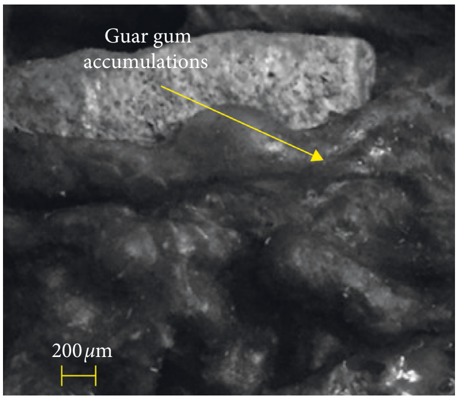


FIGURE 18: SEM of the interaction mechanism between guar gum and soil particles [55].

gum accumulations are connected between guar gum and soil particles (i.e., poorly graded sand; Gs = 2.7) [55]. van der Waals forces as physical absorption generate the weakest bonds over a long range in the SEM (Figure 18) [78].

4. Conclusions

Soil improvement methods have been intensively studied and developed over centuries. Adding cement in soils is the simplest and easiest method for soil improvement. However, the need for eco-friendly construction methods is increasing due to severe environmental concerns.

The development of numerous possible cement substitutes, including the use of biopolymers and MICP for soil improvement, has been proposed. Recent studies have shown biopolymers are used for soil improvement/stabilization and applied with their several advantages. Therefore, this study focuses on the five common biopolymers, including their development process, physicochemical properties, possible applications, and cost of each biopolymer in the market.

Several studies have shown the improvement of soil strength induced by adding biopolymers to soils. Xanthan gum-treated sand improves its cohesion and friction angle at initial and dry condition, whereas the use of xanthan gum to sand at the re-submerged condition decreases the shear strength parameter. Gellan gum-treated soil depends on the amount of clay in sand-clay mixtures. The formation of gellan gum-pure clay mixtures significantly increases their cohesion. Proper mixing of coarse particles, clay particles, and gellan gum is thus expected to enhance the optimal strengthening effects because of the combination of increased connection effect between soil particles and gellan gum. Because of the long molecule structure of agar, more agar in clayey soils improves unconfined compressive strength. Even with a slight increase in the flow rate of PAM, we need to find the optimal flow rate of polyacrylamide because of the significant flushing effect on soils contaminated by oil. Guar gum is better able to increase the unconfined compressive strength and cohesion in biopolymer-treated silt than other biopolymers such as modified starch and xanthan gum.

Although the usage of biopolymers has numerous benefits for soil improvement/stabilization, each biopolymer has different advantages to soils because the interaction between biopolymer and soil depends on their conditions such as soil type, soil-biopolymer ratios, temperature, and reaction with water. Overall, we expect to better understand the physical and chemical properties of biopolymers and then will properly apply the biopolymers that fit geographical characteristics in the near future.

Conflicts of Interest

The author declares no conflicts of interest.

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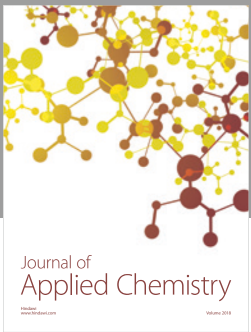
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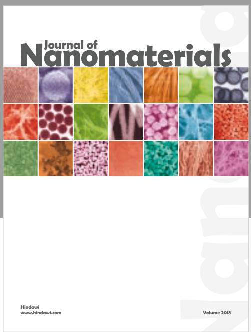
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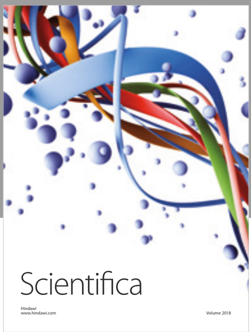
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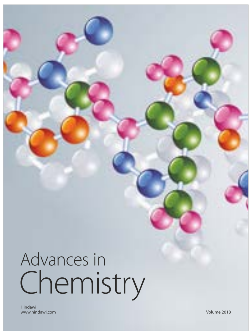
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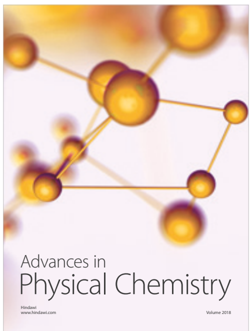
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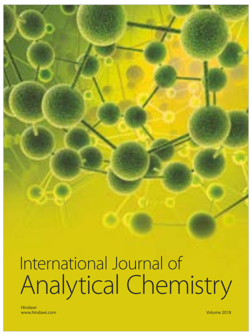
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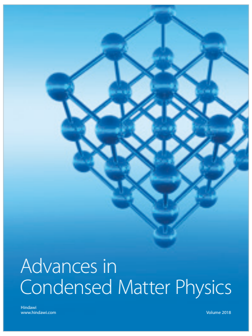
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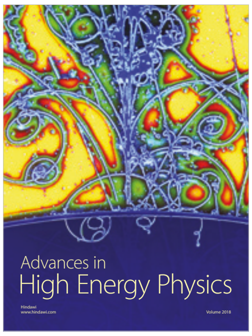
Journal of Chemistry


International Journal of Biomaterials


Advances in High Energy Physics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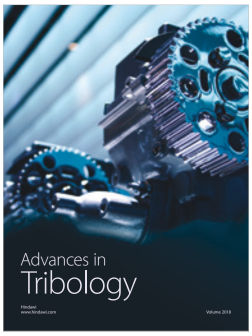
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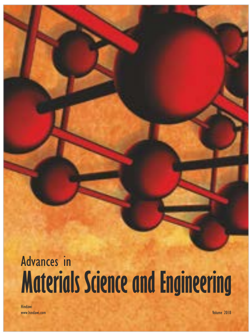
Advances in Materials Science and Engineering